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Current-induced magnetization switching in pseudo spin-valves

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Abstract

The spin transfer torque model applied in the context of a Fokker–Planck analysis (Li and Zhang 2004 *Phys. Rev.* B **69** 134416) is shown to account for a complete set of statistical data for switching times obtained with pseudo spin-valves (Fábián *et al* 2003 *Phys. Rev. Lett.* **91** 257209). Current densities of the order of 10^7 A cm^{-2} injected in Co/Cu/Co bilayers electrodeposited in nanoporous membranes gave rise to magnetization switching. Statistics could be accumulated on one single nanowire at a time: the field at which the average residence times in parallel and antiparallel configurations were equal, these times as a function of current, and the ratio of the times as a function of current and field.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

A few years ago it was predicted that the injection of a current into a magnetic structure could trigger magnetization reversal or excite magnons [1–3]. The current density of spin-polarized electrons was expected to be in the range of 10^7 A cm^{-2}. Thus, experimental verification of this prediction requires the use of point contacts to multilayers [4, 5] or spin-valves in the form of pillars of nanoscopic dimensions [6–10]. Early work encountered objections as to whether spin-polarization of the conduction electrons was indeed involved. The large currents raised the issue of spurious effects due to heating and to the Oersted field (the field induced by the current) [11]. As the experimental studies progressed [12–18], it became clear that a novel mechanism for acting on magnetization, 'current-driven magnetization switching' (CIMS), had been uncovered and that spin polarization of the conduction electrons played a determining role.

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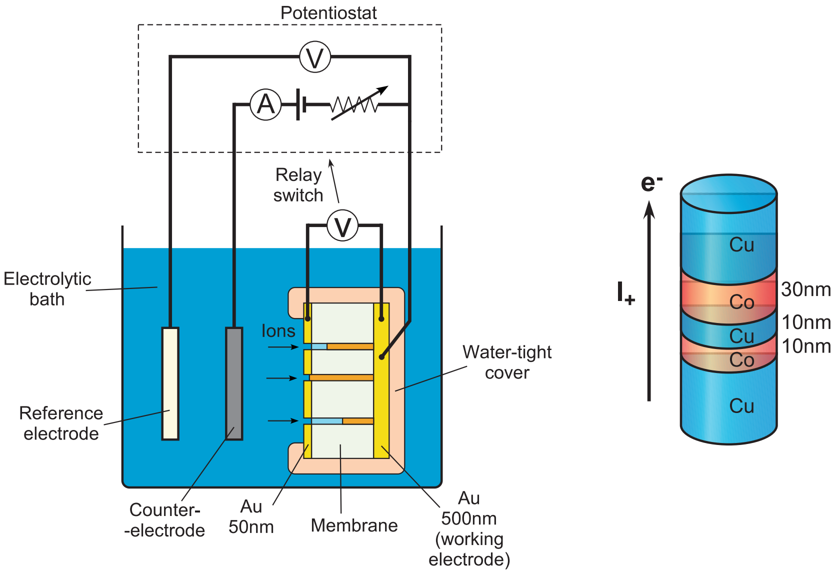

Figure 1. Left: schematic of the electrodeposition method. Right: typical geometry of a spin-valve in this study with electron flow as indicated for positive (I^+) currents.

In this paper we test the model of CIMS based on the spin transfer torque [1] by verifying how well it can account for the statistics of switching that we observed with pseudo spin-valves under large currents [19]. Namely, we show that the data can be analysed in terms of the spin-transfer torque effect included in a magnetic version of the Brownian motion description [20]. This approach of Li and Zhang is tested for our entire data set, whereas these authors used only a subset of them in their theoretical presentation. This model has the merit of being based on clear assumptions about the dynamics (the spin transfer torque term being added to the Landau–Lifshitz equation) and makes use of the standard methods of statistical physics. On the contrary, our previous account of the CIMS effect [19] contained just a rough estimate based on the assumed partial d-character of conduction electrons, and the hypothesis of one magnon created for each d-electron.

2. Sample preparation

The efficacy of the method of preparing the samples (figure 1) is crucial in this study. This is because we must take measurements at very high currents for a long time, and nanowires react to spurious transients as nanofuses! We used template synthesis [21], that is, we filled the pores of commercial membranes by electrodeposition. A double-bath technique was used to obtain Co/Cu layering. The thinnest layers that one could achieve with sufficient control to obtain giant magnetoresistance (GMR) were about 3 nm [22]. The data of [19] were taken for samples in which the Co layers were 10 and 30 nm thick, with a 10 nm Cu spacer (figure 1).

The electrical contact to a single wire was established during the growth of the nanowire. A high-impedance floating voltmeter V (figure 1) monitors the potential difference between the front and the back of the membrane. When this potential drops to zero because one wire has grown across the membrane, a relay stops the deposition. Hence, we have only one wire electrically connected between the two faces of the porous membrane. The sample mount is designed so that it can be used both for electrodeposition and for the magnetoresistance measurements. This method allowed us to produce hundreds of samples.

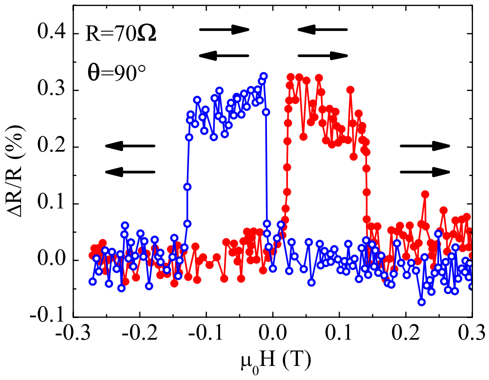

Figure 2. GMR of a spin-valve. Full (open) circles denote a field sweep up (down). Arrows illustrate the relative orientation of the magnetization of both layers.

3. Sample characterization

3.1. Monitoring well-defined magnetic states

There is nothing in our growth method that allows us to control the magnetocrystalline anisotropy of the Co/Cu layers. Application of a field during deposition was to no avail. Therefore, we had to produce many samples and use giant magnetoresistance (GMR) measurements to select those samples that had a convenient response.

The GMR profile of the selected samples is characteristic of a spin-valve (figure 2). The sharp transitions indicate simple, well-defined magnetic states. When we carry out resistance measurements as a function of time, we find switching between the two resistance values that were obtained in quasi-static measurements at low current. The resistance jump ΔR can be as much as 1 Ω! The resistance ratio $\Delta R/R$ is small because the spin-valves of our samples, about 50 nm thick, are connected to leads of Cu, about 6000 nm long.

3.2. Singling out one wire and monitoring thermal behaviour

It is well known that the distribution of switching fields in magnetic nanostructures is very broad. Therefore, if we have more than one wire connected in parallel we can see several jumps. Hence the single jump of our spin-valves attests to the fact that a single nanowire is connected.

Switching events were recorded in a time window from 1 to 8 μs after the start of the current pulse [23]. The detection set-up includes a Wheatstone bridge that allowed the precise measurements of resistance variations necessary to detect MR changes of 0.1%. Since we have independent isothermal measurements of the resistance, we can translate the resistance measurements into temperatures. We found that the thinner of our wires, those used for all of our CIMS studies, do not overheat by more than 15 K when we run through them a current with a density of the order of 10^7 A cm^{-2} (figure 3).

We can also demonstrate that we are not subjected to artefacts due to hot spots by the following consideration. We modelled the time evolution of the temperature, as a function of position and time in the nanowire, $T(r, z, t)$, by integrating the Fourier equation

$$\rho_{\mathrm{res}} J^2 + K\left(\frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2} + \frac{\partial^2 T}{\partial z^2}\right) = \rho_{\mathrm{mass}} C_p \frac{\partial T}{\partial t} \tag{1}$$

where ρ_{res} is the resistivity of the wire subjected to the current J, ρ_{mass} is its density and C_p its specific heat [24]. We concluded that there could not be hot spots along the wires. At very short times (figure 4) there could be a local point that is hotter, but then for any reasonable

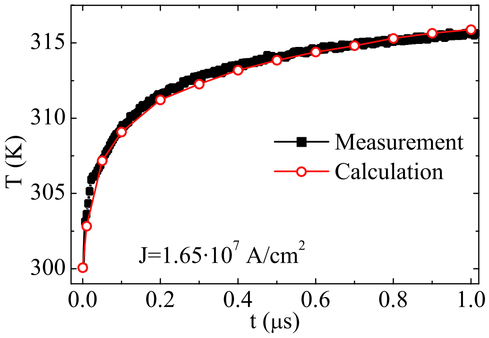

Figure 3. Temperature during the current pulse deduced from resistance (full squares) and calculated (open circles).

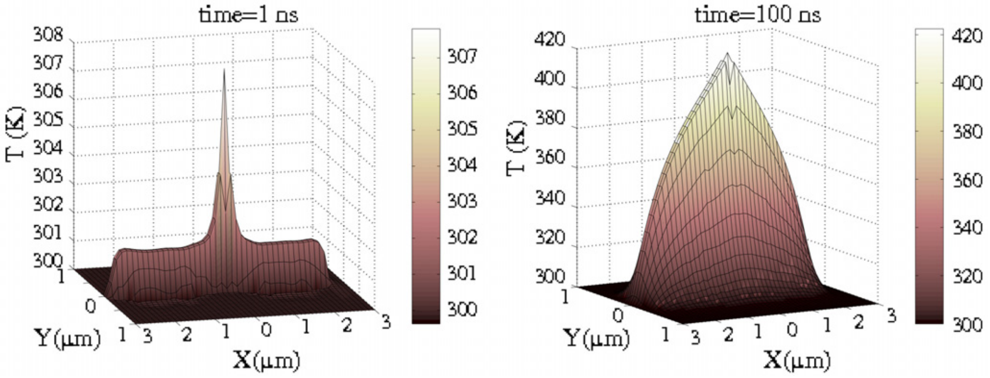

Figure 4. Simulated temperature profile along the wire, assuming a hot spot in the middle, after 1 ns (left) and 100 ns (right) of the rising edge of the current pulse.

constriction of the wire the temperature rise is small during this short time. After times longer than 100 ns, the temperature rise has spread to the whole of the wire and therefore can be detected by our resistance measurements. The times at which switching is detected (section 4) are longer than 100 ns, therefore the measured resistance at the time of switching provides a good estimate of the temperature of any point of the wire.

4. Two-state switching

In Co/Cu/Co spin-valves, there is a range of values for the applied field and for the current under which the resistance jumps randomly between the two values observed in quasi-static measurements at low current. The mean residence times were measured. The histograms present an exponential distribution (inset of figure 2 in [19]).

This simple behaviour was also observed in ultra-fine nanowires [25]. It corresponds to a Poisson process [26] and attests to hopping over a single energy barrier [27]. For a distribution of the form $f(\tau) \propto e^{-c\tau}$, the average time is given by $\langle\tau\rangle = 1/c$. We measured the *average* residence times, denoted τ_{AP}, τ_P, as a function of applied field and current. We deduced from the data of average residence times the value of the applied field $H_{sym}(I)$ at which the residence times τ_{AP} and τ_P become equal, at a set current I (figure 5). We report on a separate graph the value of the residence time $\tau_{AP} = \tau_P$ at this field as a function of current (figure 6). Finally, we consider the field dependence of the ratio τ_{AP}/τ_P at set current (figure 7).

The prevalent model for CIMS is the so-called exchange torque, or spin-transfer torque (STT) proposed initially by Slonczewski [1, 28, 29] and Berger [2, 30] independently. This

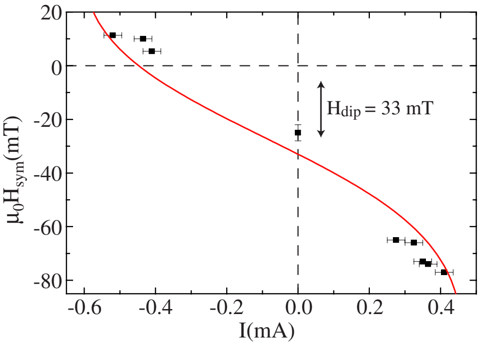

Figure 5. Applied field $H_{\mathrm{sym}}(I)$ at which $\tau_{\mathrm{AP}} = \tau_{\mathrm{P}}$. Line: prediction of (7) with $I_{\mathrm{P}} = 0.46$ mA, $I_{\mathrm{AP}} = -0.60$ mA, $\mu_0 H_{\mathrm{dip}} = 33$ mT, $\mu_0 H_{\mathrm{sw}} = 70$ mT.

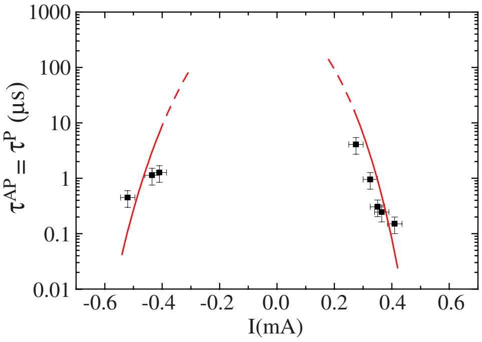

Figure 6. Mean residence times versus current, I, at $H_{\mathrm{sym}}(I)$ where $\tau_{\mathrm{P}} = \tau_{\mathrm{AP}}$. Line: prediction of equation (4) or (5) with the field H taken as $H_{\mathrm{sym}}(I)$ from equation (7) with E_0/k_{B} of 4000 K, $\tau_0 = 1$ ns.

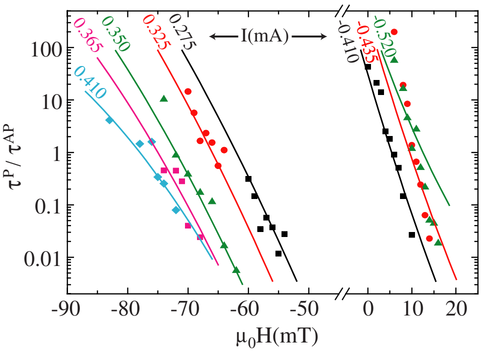

Figure 7. Mean residence times versus field at set values of the current I. Line: prediction of equation (9) with the same parameter values as in figures 5 and 6.

torque on the magnetization is added to the Landau–Lifshitz equation. It has the form

$$\frac{\gamma a_J}{M_{\mathrm{S}}} \boldsymbol{M} \times \left(\boldsymbol{M} \times \hat{\boldsymbol{M}}_{\mathrm{P}} \right) \tag{2}$$

in which $\hat{\boldsymbol{M}}_{\mathrm{P}}$ is a unit vector in the direction of the magnetization of the polarizing layer. The coefficient a_J is a measure of the strength of the interaction of the spin-polarized current on the magnetization. a_J is proportional to the current

$$a_J = a'_J I. \tag{3}$$

The Landau–Lifshitz equation for the magnetization, augmented with a spin-transfer torque, predicts an instability and magnetization reversal, if the current density is sufficiently high. This description is sufficient to account for switching currents as in [15] and [6]. However, here the experiment consists in waiting under certain set experimental conditions until the magnetization switches. It is a sort of after-effect measurement for which the coupling of the system to a thermal bath becomes critical. Li and Zhang [20] produced the first analysis of the thermally assisted magnetization reversal under the effect of this term. They searched for a solution to the stationary Fokker–Planck equation associated with the Landau–Lifshitz–Gilbert equation augmented by the STT term. They found a solution of the Néel–Brown form, from which they deduced the mean residence times

$$\tau_{\mathrm{P}} = \tau_0 \exp\left[\frac{E_0}{k_{\mathrm{B}}T}\left(1 - \frac{H + H_{\mathrm{dip}}}{H_{\mathrm{sw}}}\right)^{\eta}\left(1 - \frac{I}{I_{\mathrm{P}}}\right)\right] \tag{4}$$

$$\tau_{\mathrm{AP}} = \tau_0 \exp\left[\frac{E_0}{k_{\mathrm{B}}T}\left(1 + \frac{H + H_{\mathrm{dip}}}{H_{\mathrm{sw}}}\right)^{\eta}\left(1 - \frac{I}{I_{\mathrm{AP}}}\right)\right]. \tag{5}$$

We have taken into account in these expressions the fact that the field perceived by the free magnetic layer is the sum of the laboratory field H and the dipolar field H_{dip} produced by the fixed layer. The critical currents I_{P} and I_{AP} are given by

$$I_{\mathrm{P}} \approx \frac{\alpha 2\pi M_{\mathrm{S}}}{a'_J}, \qquad I_{\mathrm{AP}} \approx \frac{-\alpha 2\pi M_{\mathrm{S}}}{a'_J} \tag{6}$$

to the extent that we can neglect the field H and H_{dip} compared to the demagnetizing field $2\pi M_{\mathrm{S}}$. The switching field H_{sw} is the value of the field that flips the magnetization at zero temperature. The temperature was taken to be 315 K as deduced from the resistance measurement. We recognized in equations (4) and (5) the usual result for the dependence of the barrier height on magnetic field. The exponent η is taken to be 2, owing to the high symmetry configuration chosen for our experiments [31].

One might wonder whether the changes in residence times (figure 6) might be due to a temperature change, despite our control over this issue, as detailed in section 3.2. If we were to take the expressions in equations (4) and (5) to predict a change in temperature, then writing $1/kT^* = (1 - I/I_{\mathrm{P,AP}})/kT$ would yield temperatures T^* going from 600 to 1300 K for the current values of the data points (figure 6). There is certainly no so great an error in our measurement of the actual temperature of the nanowires!

Our measurement of $H_{\mathrm{sym}}(I)$ consists in setting the field so that we observed $\tau_{\mathrm{AP}} = \tau_{\mathrm{P}}$. This implies

$$H_{\mathrm{sym}}(I) = -H_{\mathrm{dip}} + H_{\mathrm{sw}} \frac{\left(1 - \frac{I}{I_{\mathrm{P}}}\right)^{1/\eta} - \left(1 - \frac{I}{I_{\mathrm{AP}}}\right)^{1/\eta}}{\left(1 - \frac{I}{I_{\mathrm{P}}}\right)^{1/\eta} + \left(1 - \frac{I}{I_{\mathrm{AP}}}\right)^{1/\eta}}. \tag{7}$$

In principle, I_{P} and I_{AP} can be obtained by measurements. However, these measurements were carried out on different samples and these critical currents must be considered as fitting parameters. The values of I_{P} and I_{AP} used for the fit are quite consistent with the observations of figure 5 in [32]. Furthermore, the critical currents can be estimated from the explicit expression of a'_J deduced from the torque expression obtained by Slonczewski [1, 28, 29, 33]:

$$a'_J = \frac{g}{\gamma} \frac{1}{|e|Sd} \frac{g_{\mathrm{L}}\mu_{\mathrm{B}}}{M_{\mathrm{S}}} \tag{8}$$

with g defined in [1], g_{L} the Landé factor taken to be 2, μ_{B} the Bohr magneton, d the thickness, S the surface area of the magnetic layer and e the electron charge. Hence $|a_{J,\mathrm{crit}}| \approx \alpha 2\pi M_{\mathrm{S}}$ implies a current of the order of 1 mA, which agrees quite nicely with the values chosen for the fit of $H_{\mathrm{sym}}(I)$ (figure 5). In the fitting procedure, the field H_{dip} simply translates the curve obtained for $H_{\mathrm{sym}}(I)$. The value was not taken as a free parameter but instead was determined as the centre of the minor loop measured at low current.

We put the field $H_{\text{sym}}(I)$ (equation (7)) in equation (4) to get a prediction for the dependence of the mean residence times $\tau_{\text{P}} = \tau_{\text{AP}}$ on current. We can account for the data (figure 6) using E_0/k_{B} of 4000 K and τ_0 of 1 ns. These are reasonable values compared to those found for Co particles of similar sizes by magnetic measurements on micro SQUIDs [34].

Finally, we challenged the model further by comparing the predictions of equations (4) and (5) with the data for the ratio $\tau_{\text{P}}/\tau_{\text{AP}}$ (figure 7). Again we can account for the data with the same set of fitting parameters $(E_0, I_{\text{P}}, I_{\text{AP}}, \tau_0)$. The slope on the graph can be expressed by writing $H = H_{\text{sym}}(I) + \Delta H$ in equations (4) and (5), and developing to first order in ΔH

$$\ln \frac{\tau_{\text{P}}}{\tau_{\text{AP}}} = -4 \frac{\Delta H}{H_{\text{sw}}} \frac{E_0}{k_{\text{B}} T} \sqrt{1 - \frac{I}{I_{\text{AP}}}} \sqrt{1 - \frac{I}{I_{\text{P}}}}. \tag{9}$$

Only the parameter E_0 enters in the data (figure 7) once $H_{\text{sym}}(I)$ has been accounted for (figure 5). The latter, on the other hand, is independent of E_0 and τ_0. So the full set of data on residence times presents stringent requirements for the fitting procedure! Figures 5–7 are different from those published in [19] because here the fitting curves come from the STT model. In [19], only a fit to $\tau_{\text{P}}(I) = \tau_{\text{AP}}(I)$ was attempted with a model of magnon excitation[1].

5. Conclusion

This paper discusses the interpretation of experimental results [19] on current-induced magnetization switching (CIMS) in spin-valves. The samples consisted of singly contacted nanowires. The nanowires included a Co/Cu/Co spin-valve embedded in the middle of a Cu nanowire. The magnetic configurations of these ferromagnetic nanostructures were monitored by magnetoresistive measurements, relying on the GMR of the spin-valves. Joule heating of the wire under current was measured.

- We show that an analysis of the thermal behaviour of these nanowires can exclude the presence of hot spots. The fact that magnetization switching may occur over times much longer than the time needed to thermalize the nanowire is further evidence that Joule heating is not a spurious cause of CIMS. Likewise, the switching back and forth between two values of resistance rules out the effect of the field induced by the current as a spurious cause of CIMS.
- We show that the full set of switching data obtained with our pseudo spin-valves ([19]) can be interpreted in terms of the spin transfer torque (STT) model using the statistical analysis (Fokker–Planck) proposed by Li and Zhang. Whereas these authors took our $H_{\text{sym}}(I)$ data, here we fit consistently $H_{\text{sym}}(I)$, $\tau(I)$ and $\tau_{\text{up}}/\tau_{\text{down}}(I)$.

The present analysis has the merit of covering all features of our switching data (figures 5–7). The model of excitations of magnons [35, 36] cannot be ruled out. It gives a prediction for $\tau_{\text{AP}}(I) = \tau_{\text{P}}(I)$. The fits are approximate in both cases and the fitting parameters have reasonable values. Further experimental work is needed in order to discriminate between the two models. In particular, one has to take into account the fact that the STT model predicts different regimes [37], including precession switching and ‘incoherent’ switching which may be close to the prediction of the magnon excitation model.

Acknowledgments

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[1] Figures 3 and 4 of [19] contained lines that were simply guides to the eye.

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